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SOLAR ELECTRIC SPACE MISSION ANALYSIS

Progress Report for the Period

1 April through 30 June 1967

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I. INTRODUCTION

During the period 1 April - 30 June 1967 research on solar electric space missions concentrated in the following areas

(1) continuing developmen of Gordon 1 - 2, heliocentric optimization program, and Item, n-body integration program.

(2) production runs on the Jupiter flyby solar electric mission using Gordon 1.

Dr. C. N. Gordon, who has been chiefly responsible for the development of Gordon 1, has left Princeton to return to England. Work on the program (which is close to completion) is being continued by George Hazelrigg, assisted by Mrs. Alexandra Schulzycki. Mr. Hazelrigg has made sufficient modifications to the program that it will be referred to as Gordon 2.

Mr. A. E. Miller, programmer, is leaving as of 31 July.

The production runs on Gordon I have been accomplished by Mrs. Schulzycki. Mr. John Campbell of AMA is responsible for the development of ITEM.

II. SPACEFLIGHT TRAJECTORY ANALYSIS

The emphasis in this program during this period has been on continuing development of Gordon and ITEM programs.

A. Gordon 2.

George Hazelrigg is continuing the development of the Gordon program. He has made sufficient modifications that the program is now referred to as Gordon 2. It is expected that this program will be complete by the end of July.

Modifications to Gordon 1, resulting in the Gordon 2 program, include:

(1) Extension of the booster subroutine to include additional launch vehicles. This subroutine has been rewritten in a form which permits easy addition of new launch vehicles. In addition to the SLV3C/ Centaur, the

SIB/ Centaur, Titan IIIC (1207) and Titan IIIC/ Centaur vehicles are presently in the subroutine and a selection is made by specifying the appropriate number for the input variable NBSTR.

(2) Provision to optimize the magnitude of the hyperbolic velocity. Gordon 2 now has the capability to determine, for a given launch vehicle, the hyperbolic velocity which maximizes the payload. The optimization is based on the necessary condition

$$\frac{dm}{dv_h} = -\frac{P}{\sigma} \qquad \frac{1 + \gamma_t}{m_f(1 + \gamma_t) - \gamma_s - \gamma_t - m_g}$$

where

P = magnitude of primer vector at launch

σ = final value of Lagrange multiplier associated with mass

γ_t = tankage factor

γ_s = structure factor

m_g = powerplant mass

m_f = final mass

The derivative $\frac{dm}{dv_h}$ is a function of the launch vehicle.

(3) Provision for a finite hyperbolic velocity at the arrival planet. The magnitude of the hyperbolic velocity at the destination may be specified and its direction may be either specified or optimized. The solution is applicable to the problems of a planetary flyby with a constrained velocity and of a high thrust capture maneuver at the destination.

(4) Improved integration. The integration has been improved from second order to fourth order in the predictor-corrector scheme. In addition, provision has been made to allow more accurate corrections in the corrector part of the integration routine. The result has been quicker and more uniform convergence, particularly for long missions to the outer planets.

(5) Improved iteration. The iteration routines of Gordon 1 were improved for greater stability through the inclusion of an automatic

correction limiter. The present routine is, for many missions, sufficiently powerful to obtain converged trajectories from any reasonable initial guesses (for example, 0.5 for all adjoint variables) thus eliminating the necessity for elaborate methods of obtaining accurate initial guesses.

(6) Improved SOLAR subroutine. Subroutine SOLAR is used to compute the power output of a solar-electric array as a function of heliocentric radius. Presently employed (from Gordon 1) is a power series representation accurate for $0.5 \leq R \geq 10$ AU. A new expression

$$P = \frac{R - .3}{.7R^3}$$

has been added which is not as accurate as the power series within the appropriate range, but does provide the necessary accuracy for $R > 10$ required to perform mission analyses to the outer planets.

The status of the Gordon 2 program can be summarized as follows: it is a working program which has been checked over a reasonable range of missions. The program has been given to representatives at NASA MSFC and IITRI for trial usage and evaluation.

B. ITEM

Mr. John Campbell of AMA has been in charge of the Princeton version of the ITEM program. The principle effort during this period has been the adaption of a new and more accurate ephemeris tape (JPL Development Ephemeris 19).

This ephemeris has been converted to the 360 and routines for its use have been incorporated into the 360 ITEM program. The data for the Sun, all planets through Pluto, and the Earth's moon from 1970 through 1999 have been included.

All programs are being converted to the IBM 360/50 since the 7044 and possibly, 7094 will leave during the coming academic year.

III. SOLAR ELECTRIC MISSION ANALYSIS

The main effort in mission analysis during the period 1 April - 30 June has been the further study of the Jupiter flyby mission. It will be recalled (Ref. 1) that the trajectories computed optimized power level, jet velocity and hyperbolic excess velocity (C_3) as well as thrust program. Vehicle characteristics used were prescribed by JPL. During this period parameters were systematically varied to determine the effect upon the net mass at Jupiter.

Figure 1 shows the variation of net mass versus C_3 for a number of flight times. In this case the optimum is quite flat. Figure 2 shows the effect on net mass of an improvement in powerplant specific mass over a range of flight times. The original trajectories were computed using $\alpha =$ .03 Kg/w. The effect of a reduction to $\alpha =$ .027 and .024 is shown. For this plot, trajectories were reoptimized using the new value of α. Over the range investigated the effect on net mass is for practical purposes, linear with α, independent of flight time. Figure 3 shows the effect of an improvement in overall engine efficiency over a range of flight times. For this plot, the vs V_J curve, originally provided by JPL, was shifted upward by 10% and 20%. The trajectories were then re-optimized. Again the improvement appears to be relatively independent of flight time. All of these results were computed for Mode 1 (direct) trajectories to Jupiter.

To determine the effect upon net mass of variations in power level, jet velocity, and hyperbolic excess velocity (C_3) two example trajectories were chosen. The first of these is a Mode 1, 600 day flight with net mass of about 181 Kg. A plot of a similar direct trajectory is shown in Fig. 4 and the trajectory profile is shown in Fig. 5. Sensitivity of net mass to three optimized parameters is shown in Fig. 6. Optimization with respect to power is especially sharp.

The other trajectory chosen for study was a Mode 3, 900 day flight with net mass of about 355 Kg. A plot of a similar trajectory is shown in Fig. 7 and the trajectory profile in Fig. 8. Sensitivity of the net mass to

P, VJ, and VH is shown in Fig. 9. Again, the optimum power level is quite sensitive.

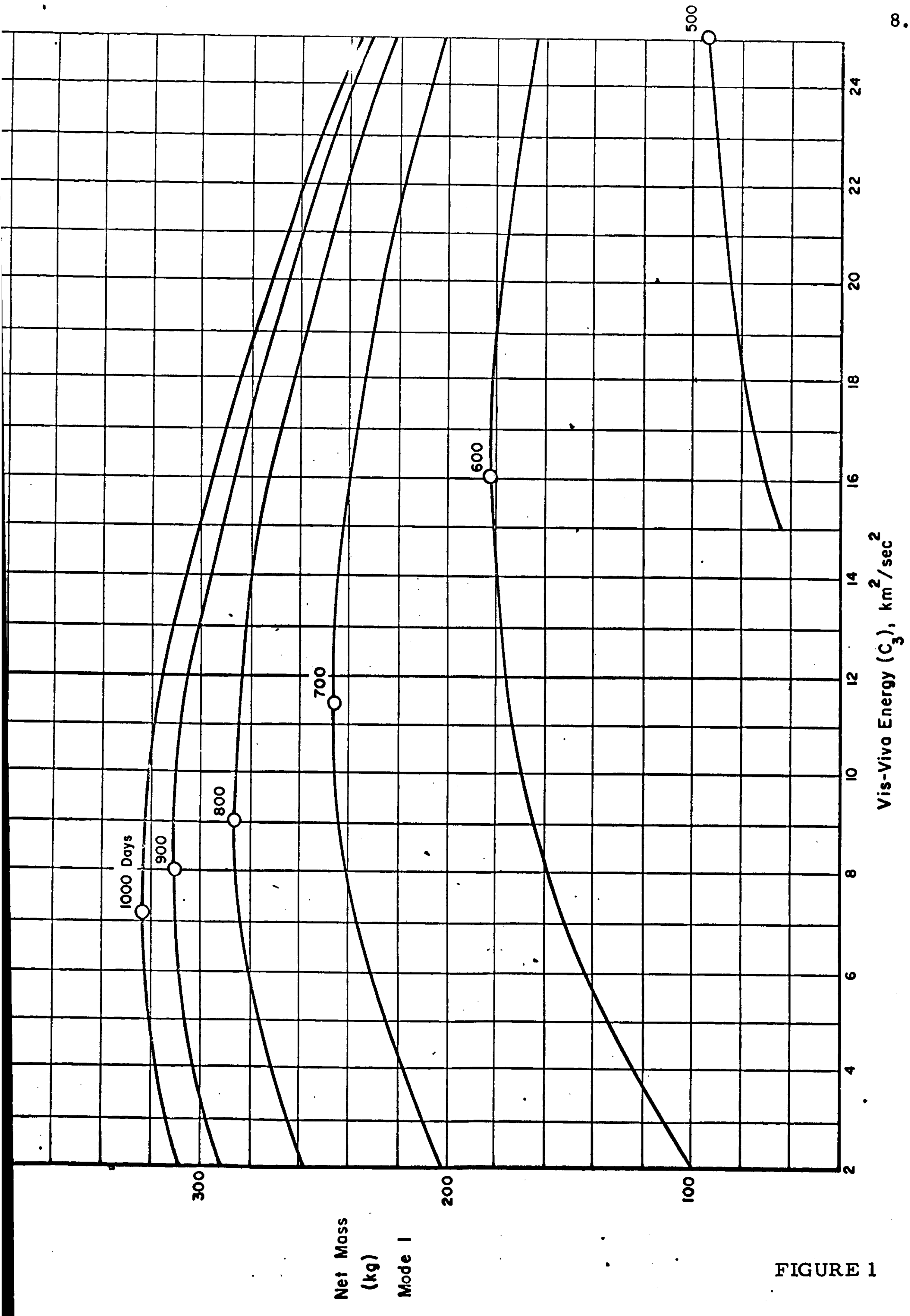

Net Mass
(kg)
Mode I
Vis-Viva Energy (C_3), km^2/sec^2
1000 Days
900
800
700
600
500
100
200
300
2
4
6
8
10
12
14
16
18
20
22
24

FIGURE 1

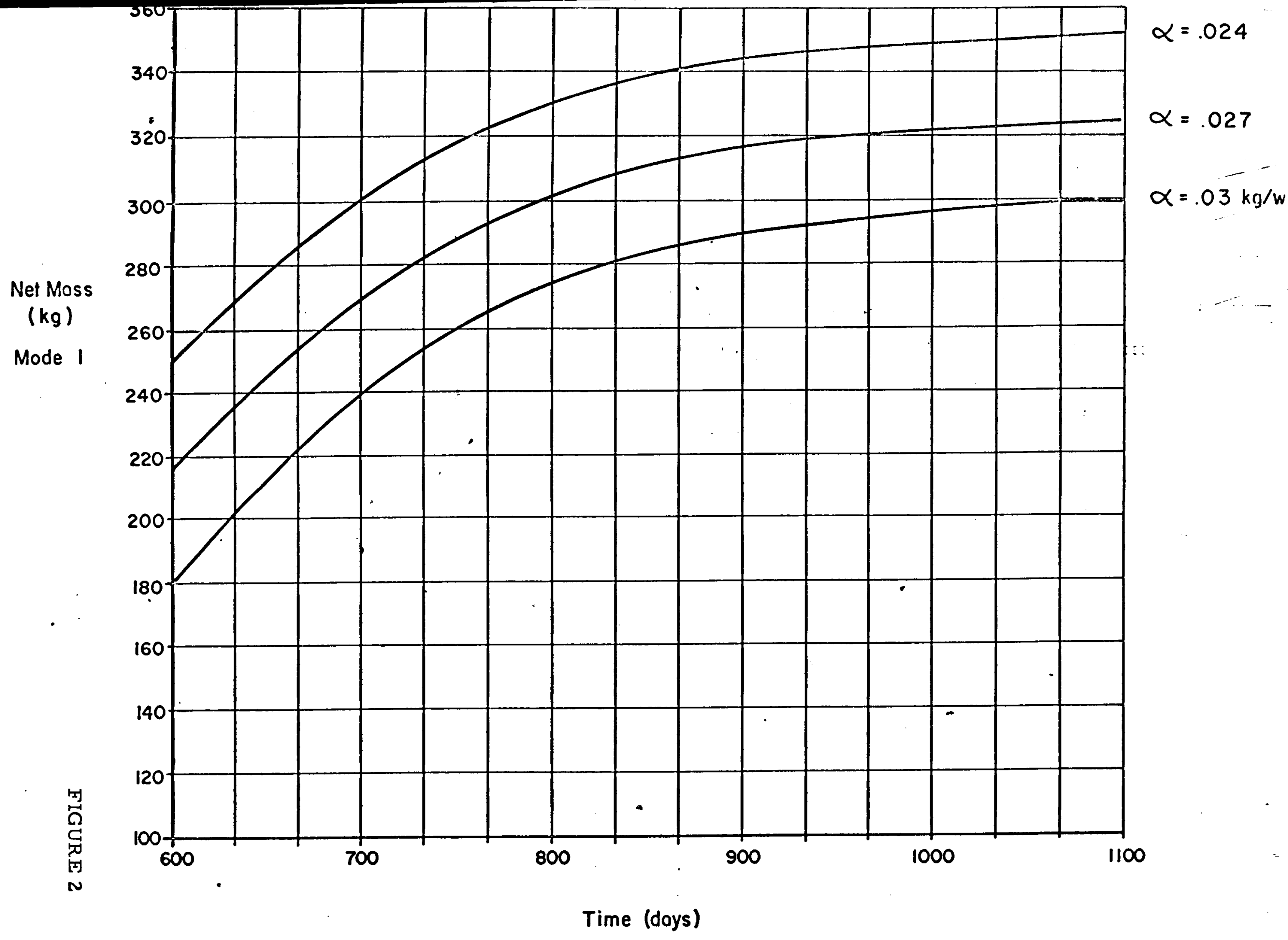

Net Moss
(kg)
Mode 1
360
340
320
300
280
260
240
220
200
180
160
140
120
100
600
700
800
900
1000
1100
Time (days)
α = .024
α = .027
α = .03 kg/w

FIGURE 2

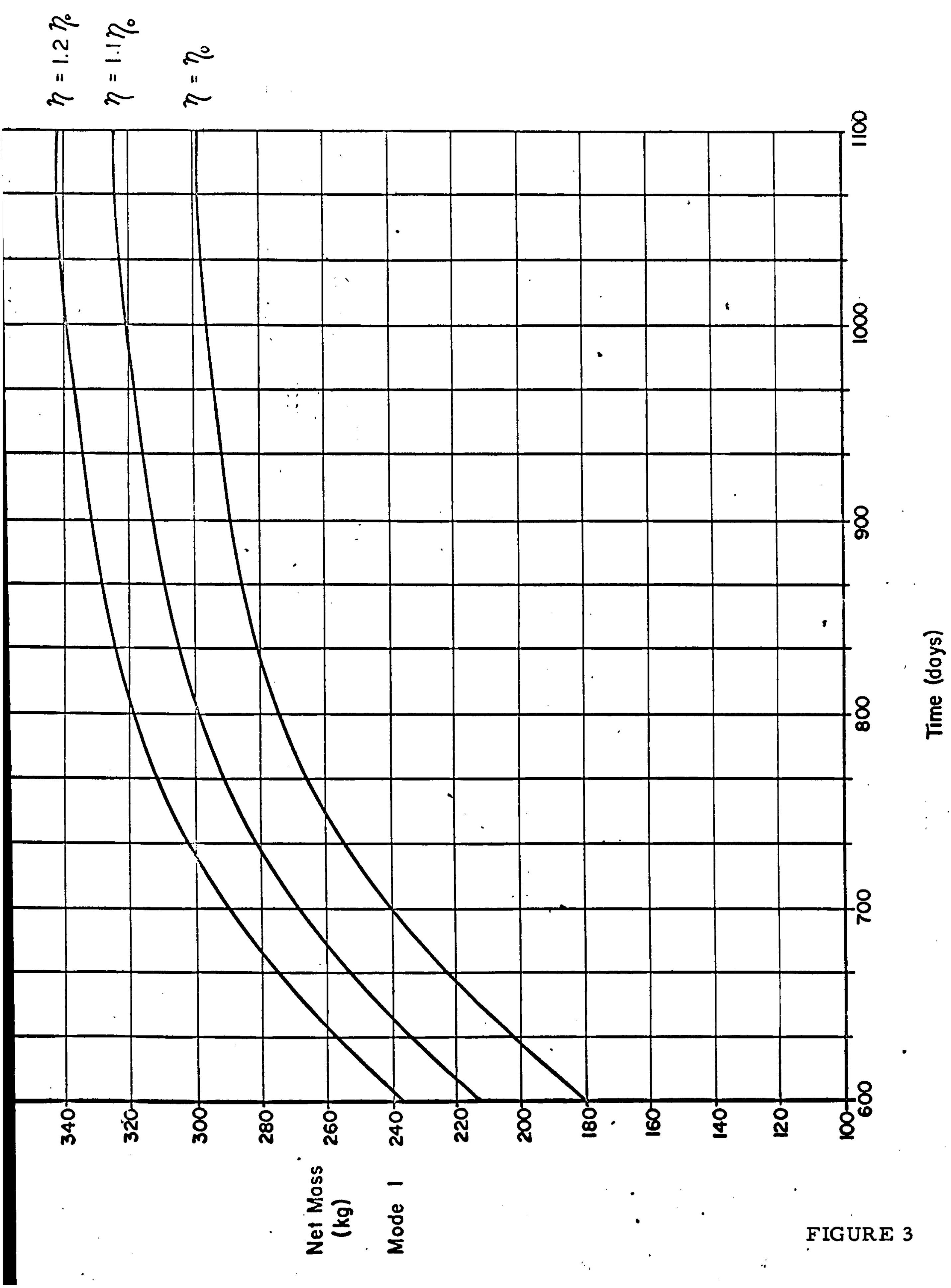

$\eta = 1.2\,\eta_0$
$\eta = 1.1\,\eta_0$
$\eta = \eta_0$
Net Mass (kg)
Mode I
340
320
300
280
260
240
220
200
180
160
140
120
100
600
700
800
900
1000
1100
Time (days)

FIGURE 3

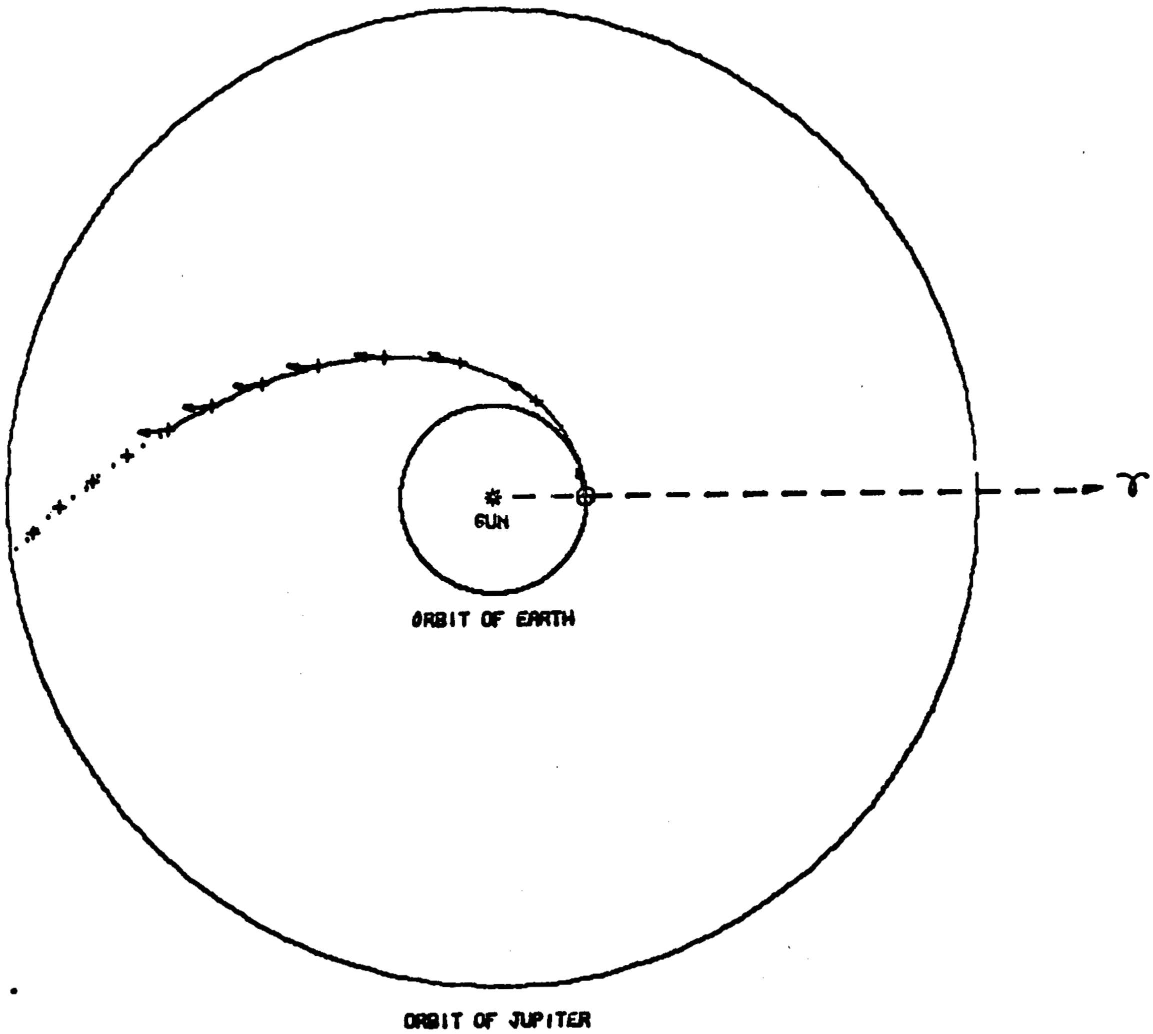


FIGURE 4

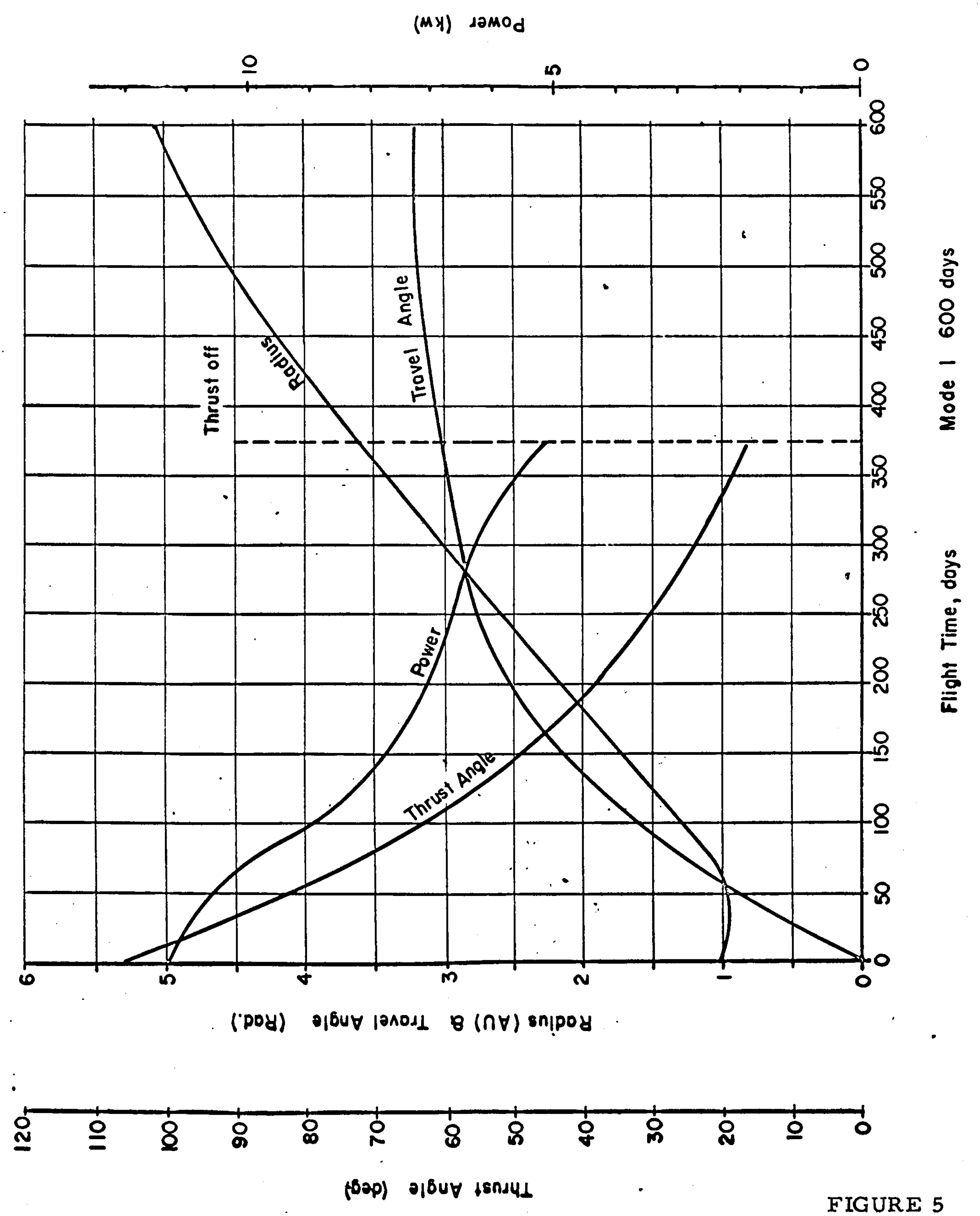

Power (kw)
Radius (AU) & Travel Angle (Rad.)
Thrust Angle (deg)
Flight Time, days
Mode I 600 days
Thrust off
Radius
Travel Angle
Power
Thrust Angle

FIGURE 5

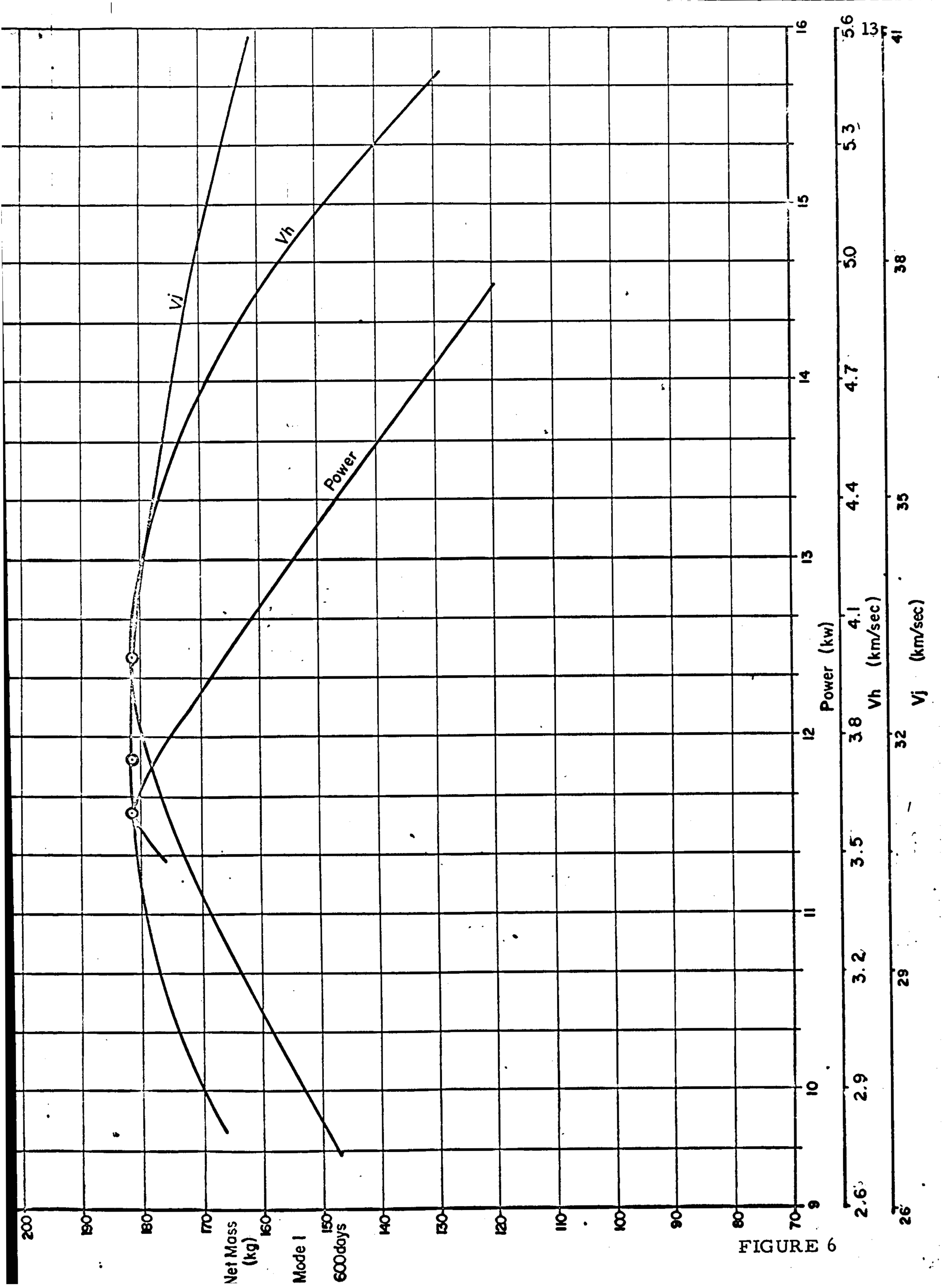

Net Mass
(kg)
Mode I
600days
200
190
180
170
160
150
140
130
120
110
100
90
80
70
Power (kw)
9
10
11
12
13
14
15
16
Vh (km/sec)
2.6
2.9
3.2
3.5
3.8
4.1
4.4
4.7
5.0
5.3
5.6
Vj (km/sec)
26
29
32
35
38
41
Vj
Vh
Power

FIGURE 6

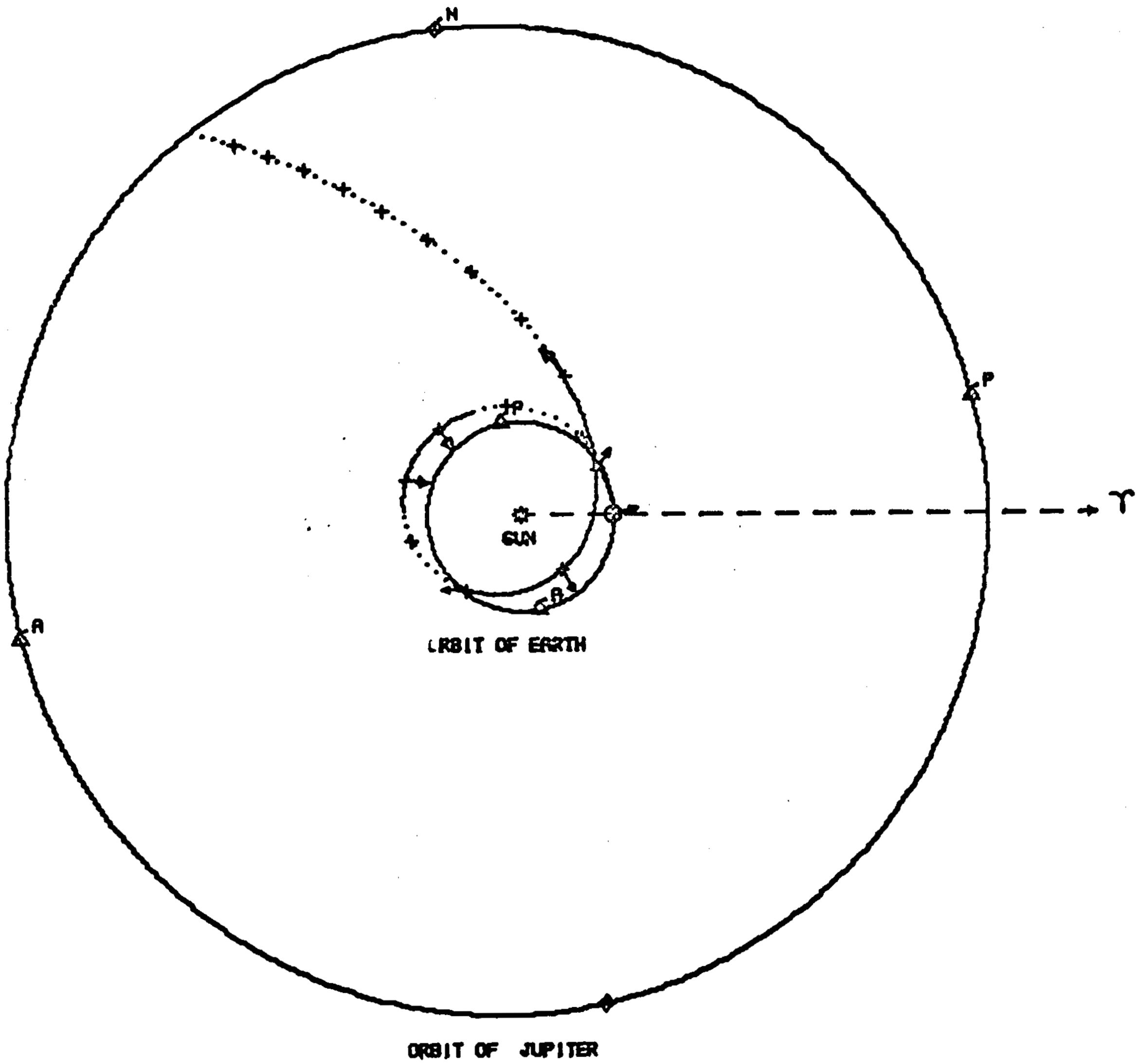


FIGURE 7

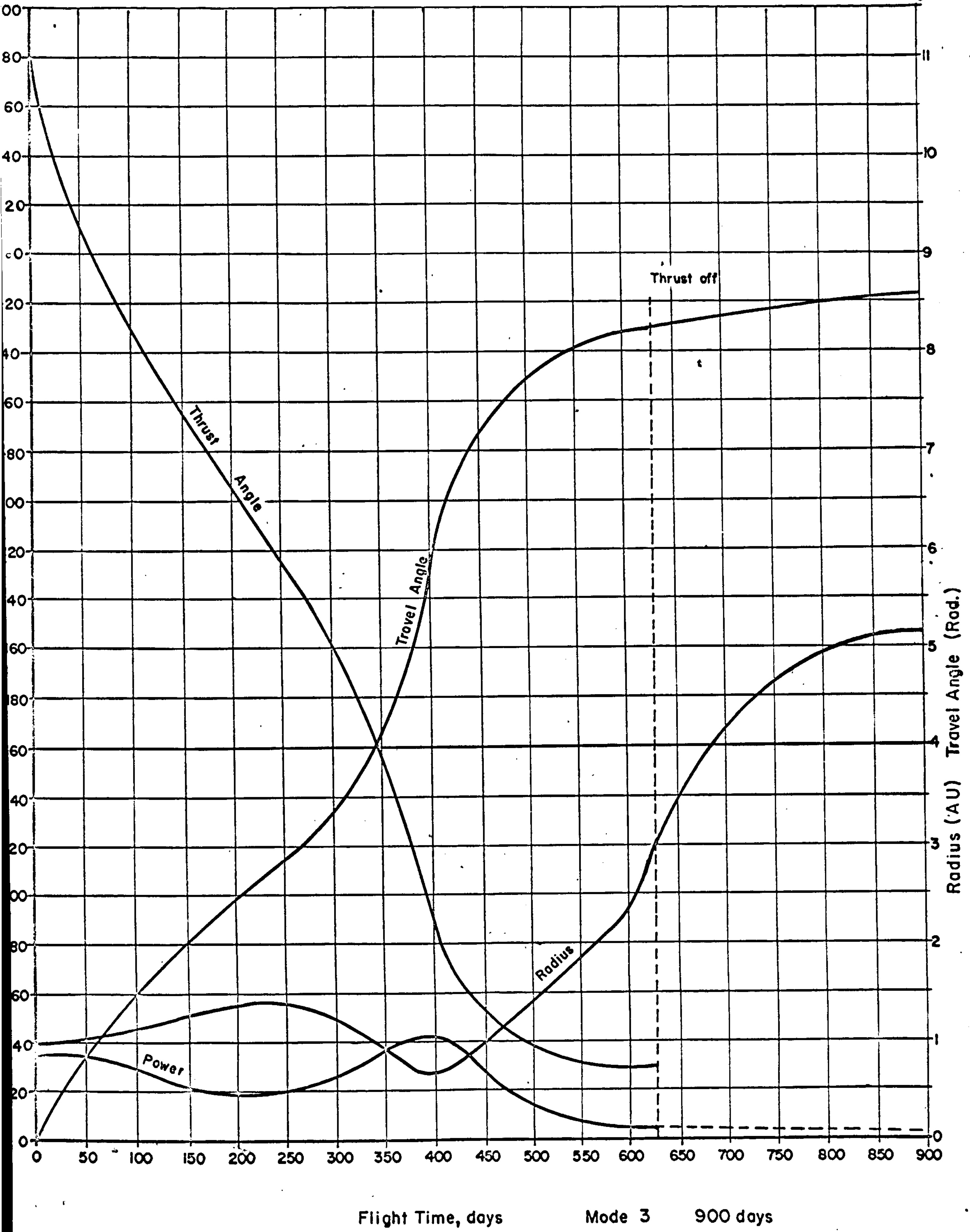
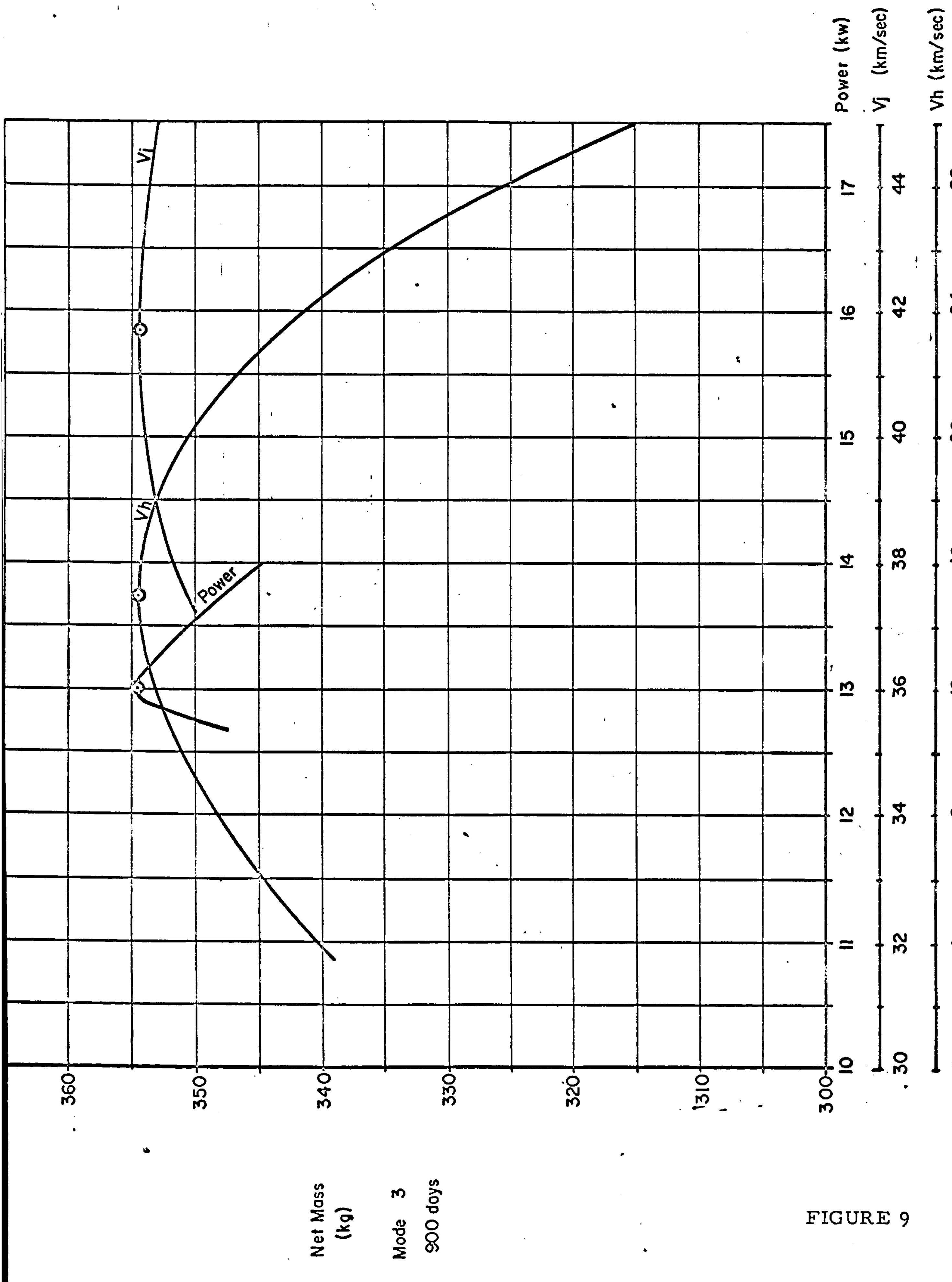

Thrust off
Thrust Angle
Travel Angle
Radius
Power
Radius (AU) Travel Angle (Rad.)
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
0
1
2
3
4
5
6
7
8
9
10
11
Flight Time, days
Mode 3
900 days

FIGURE 8



Power (kw)
Vj (km/sec)
Vh (km/sec)
Vj
Vh
Power
Net Mass
(kg)
Mode 3
900 days
360
350
340
330
320
310
300
10
11
12
13
14
15
16
17
30
32
34
36
38
40
42
44
0
.4
.8
12
16
20
24
28

FIGURE 9